# Effects of Offshore Forcing in the Nearshore Environment

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## LONG-TERM GOALS

The broad objective of this project has been to extend our understanding on the role of large scale offshore forcing, including baroclinic tides, in nearshore dynamics. From this understanding we aim to develop modeling approaches that, combined with offshore baroclinic models, can account for the effects of offshore internal wave forcing on the circulation and sediment transport in the coastal zone.

## OBJECTIVES

Specifically, the work has aimed towards addressing two questions:

1. How is offshore baroclinic tidal energy manifested in the nearshore environment, i.e.what is the transfer function between internal tides and nearshore currents?

2. What is the role of baroclinic tidal energy in nearshore circulation and, subsequently, on sediment transport?

The work has focused on real-time observations combined with event-driven sampling methodology to highlight the role of offshore tidal and wave forcing in the circulation and transport dynamics in the nearshore. Important secondary objectives include validation of the Delft3D model in capturing the effects of baroclinic forcing and predicting hydrodynamic circulation and sediment transport in the spatially complex environment posed by a carbonate reef.

# Report Documentation Page

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## APPROACH

Field observations examining the nearshore response to offshore forcing have been carried out on the south shore of Oahu, focusing on the Kilo Nalu Observatory (www.soest.hawaii.edu/OE/KiloNalu/ ). Development of a nested, high-resolution numerical model for the study region has been underway in parallel with the field operations.

Kilo Nalu includes cabled nodes at 12 and 20 m depths (~0.4, 0.8 km from the shoreline, respectively). The existing cabled instrument array includes ADCPs and thermistor chain moorings at each node and a near-bed turbulence microprofiler and basic water property measurements (T, S, DO, Chl, turbidity) at the 12m site. Details of the observatory infrastructure are outlined in Pawlak et al (2009). The ONR work has also included deployment in 2009 of a string of bottom-mounted temperature and pressure sensors extending to 100 m depth that will enable measurement of baroclinic flow structure across the shelf. A series of focused field observations were carried out in summer 2007 using cabled and autonomous instrumentation (figure 1) combined with AUV based spatial sampling. An offshore deep water profiling mooring was deployed between June and November 2007 in collaboration with M. Alford (UW APL) although this provided limited data due to a profiler failure. Efforts have focused on analysis of the 2007 data sets along with ongoing extended observations at Kilo Nalu.

A nested modeling approach was pursued with the purpose of resolving the nearshore internal tide. A 1 km Princeton Ocean Model (POM) run spanning the Molokai Channel was carried out which successfully captured the main features of the offshore internal tide as it propagates westward from the primary generation site on the east side of the channel. Several approaches were examined for modeling inner-shelf baroclinic processes using Delft3D.

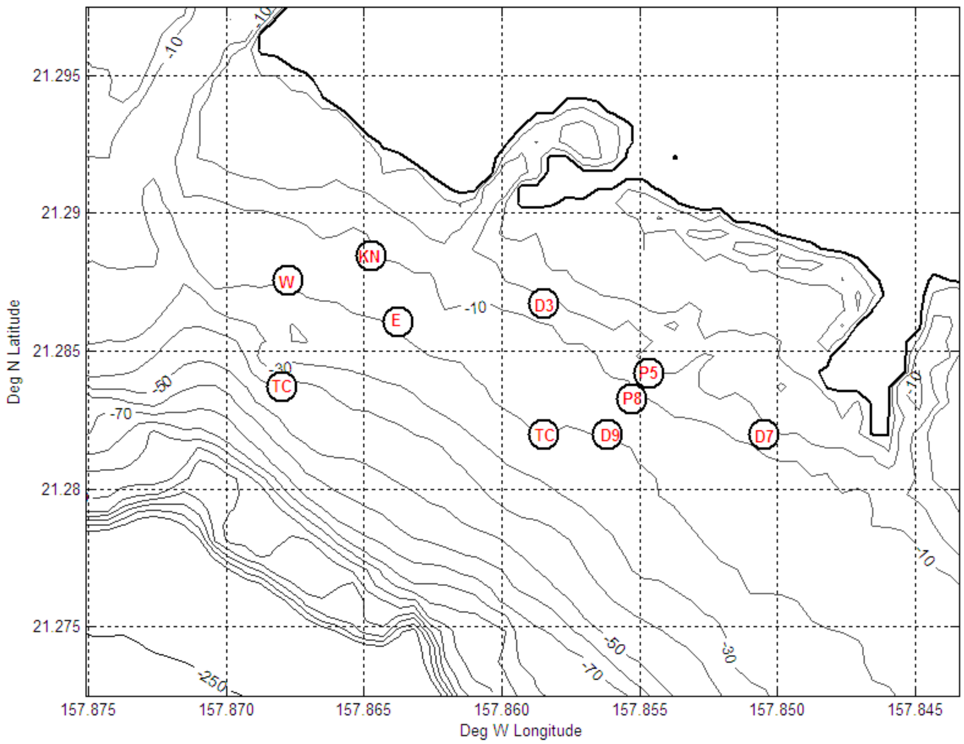


***Figure 1 – Summer 2007 field instrumentation array. Kilo Nalu cabled array (KN) is at upper left. P5, P6: Aquadopp PUV current profiler; D3, D7, D9: Aquadopp PUV current meter; E, W: ADCP current profiler; TC: T-chain.***

As an extension to the focus on offshore forcing effects in the nearshore and as a follow-on to earlier funded ONR work (N00014-03-1-0486), we have also carried out analysis of field data examining dynamics of wave-driven flow over irregular roughness. These observations make use of profiling techniques that enable spatial resolution of the wave boundary layer structure over a 2 m stretch of reef.

Two postdoctoral researchers Judith Wells and Jeremy Bricker, and two graduate students, Marion Bandet and Greg Rocheleau, have been supported in part by this ONR project. The project is also providing partial support for a research technician, Kimball Millikan, who has participated in field operations and experiment design.

## WORK COMPLETED

The initial stages of the project focused on development of the broader scale model components, collection of field observations, along with statistical analysis of earlier time series data from Kilo Nalu. Recent work has focused on analysis of the observations carried out in summer 2007, targeted at resolving the region extending from the surf zone to offshore depths. Modeling efforts have focused on development of a nearshore model component. Development of a three-dimensional model capable of accurately reproducing baroclinic flow using the DELFT3D platform has highlighted a number of challenges. In particular, the boundary conditions on flow and stratification introduce significant constraints that can lead to spurious results if not dealt with carefully.

## RESULTS

### *i) Modeling*

Conclusive interpretation of the spatial structure requires a functional model capable of capturing the influence of offshore baroclinic motions as well as frictional interactions with the complex coastline and bathymetry. The principle challenges in modeling the baroclinic features are associated with the broad range of depths (4000 m offshore to 10 meters and less nearshore) that must be resolved. The regional internal tide has been successfully described using the Princeton Ocean Model with 1 km horizontal grid resolution and 61 sigma levels. Runs have been made for the dominant semi-diurnal and diurnal constituents using TPXO6 to prescribe the barotropic forcing at the POM grid boundaries. The initial efforts focused on a traditional nesting scheme using POM results to force a local Delft3D baroclinic model. The barotropic case was successfully simulated down to the highest resolution inner grid (10m), however, the baroclinic solution was persistently susceptible to instability as model errors at the course grid boundaries quickly migrate into the mid and inner grids.

Domain-decomposition was also examined, in which two-way nesting is used for successively finer grids leading to the nearshore. A disadvantage with this approach is the need to generate a large number of nested domains in order to negotiate the abrupt transition from deep to shallow water over the steep slopes of Mamala Bay. This method was also subject to instability associated with mismatches at the grid domain boundaries. These mismatches are inevitable as the POM simulations do not capture the details of the internal tide generated within the higher resolution Delft3D domains.

An alternative strategy was investigated, using Delft3D at a large scale to first achieve a stable regional simulation that includes the baroclinic tide generation sites, before nesting in a higher resolution coastal model. A 1-2 km varying resolution, vertically varying sigma grid was developed with open boundaries in the Kaua`i and `Alenuihaha Channel and to the north and south of Oahu and Maui.

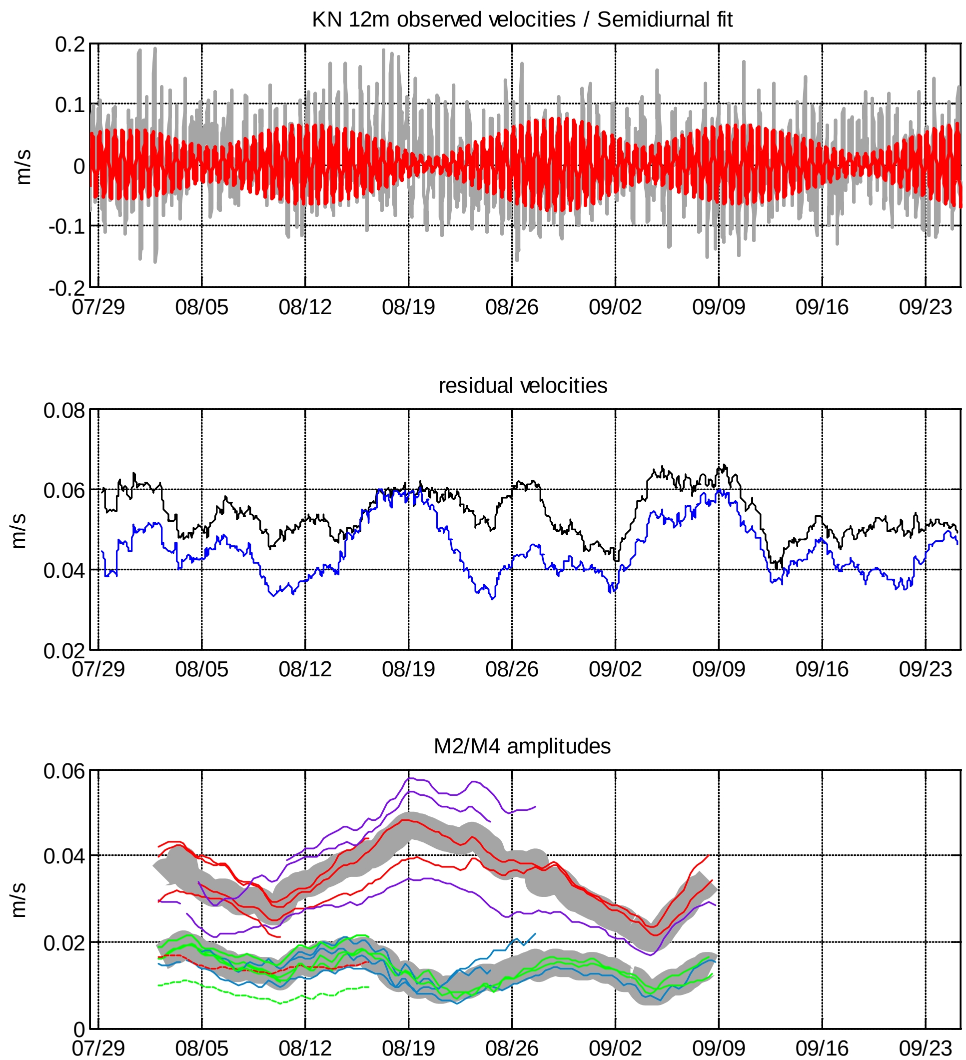


***Figure 2 – Top: Kilo Nalu 12m alongshore currents (depth-averaged) for Aug/Sept '07. Predicted velocity from harmonic analysis with semidiurnal bandpassed observed sea surface height (SSH) is overlaid. Center: variance of 'unexplained' residuals from SSH (black) and semidiurnal bandpassed SSH regression, illustrating significant and prolonged deviations from either prediction method. Bottom: M2 (red/purple), M4 (green/blue) amplitudes from autospectra for 2007 observational array. Array averages are shown in gray. Temporal variability is consistent across the array. Increases in M2/M4 energy are reflected in increased residuals.***

Space-varying diffusivity parameters were used to achieve artificially high dissipation at the boundaries. Profiles obtained from Station Aloha were used to define initial conditions and boundary conditions for temperature. Salinity transport was not activated in these simulations. Simplified typical atmospheric conditions were defined to provide a surface heat and radiation flux. Significant instabilities developed at the boundaries with jet-like structures occurring at the open boundaries where steep topography existed. The model domain was expanded to have open boundaries at more gradual topographic locations as described above. This reduced instabilities at the boundaries, although total exclusion of steep topography at the open boundaries would require a large grid encompassing most of the island chain and practical limits on computational time did not support further grid expansion. Shortly into the model run, reflections of internally generated baroclinic energy were prevalent at the boundaries. Despite the use of a dissipative layer, mismatches between prescribed boundary conditions and internally computed conditions were enough to cause further instability in the model.

Two options currently exist within Delft-3D to deal with this issue; a ramp up of boundary conditions after outgoing flow and a dissipative layer. The slackening of inflow conditions is primarily designed for estuarine flow and not regional ocean models. Significant effort was put into both of these options, and some improvement was observed, but instabilities were consistently beyond an acceptable level. Further progress on this topic will likely require significant modification of the Delft3D source code, preferably with dedicated participation of Delft3D personnel.

***ii) Observations***

Nearshore currents measured at the 12 m Kilo Nalu site (Figure 2, top) show a high level of variability with a significant stochastic component that is not correlated with the surface tide. Harmonic analysis of hourly averaged currents at 12 and 20 m at Kilo Nalu from June 2008 to February 2009 using M2 and K1 tidal frequencies accounts for only about 30% of the total variance. This is consistent with analysis offshore in Mamala Bay by Eich et al. (2004) which could only account for 60% of the semidiurnal internal tide energy using tidal frequencies. In contrast, M2 and K1 account for 72% of the variance in surface height over the data record extending back through 2007. Including the next four tidal constituents accounts for over 90% of the variance in surface height. One of the key objectives has been to establish the mechanisms that drive the variability in currents in order to achieve accurate and predictive modeling. The working hypothesis has been that the high variability observed in nearshore velocities is related to the velocity field associated with strong offshore baroclinic motions.

Regression fits to the M2 component of the 10m alongshore velocity at Kilo Nalu using the surface tidal signal from Honolulu Harbor have been used to isolate periods of high variability that are not coherent with the surface tide (Figure 2). The regressed tidal signal and observed M2 component show periods of close agreement, along with significant periods where there is a strong M2 component that is not accounted for by the surface signal. Complex demodulation of the velocity time series similarly indicates that these periods are associated with shifts in M2 phase over timescales of weeks. These observations suggest that while the currents are essentially at an M2 frequency, shifts in phase result in significant variability in the currents relative to the surface tide and is reflected by poor correlations with M2 and sea surface height over long time windows.

Analysis of data from the summer 2007 array (Figure 1) examined the spatial structure of the nearshore variability in currents. Rotary spectral analysis of the nearshore instrument array identified high spatial variability in flow structure (Figure 3) with significant temporal variability (Figure 2, bottom). Rotational sense is seen to vary over short distances, suggesting that changes in locally generated vorticity may play important roles in flow structure. The rotational sense also varies considerably with time at the M2 frequency. EOF analysis of the spatial velocity data, however, indicated that nearly 75% of the variance was accounted for by a single mode, which was characterized by uniform along-isobath flow (Figure 4). The second mode, which corresponded to a convergent-divergent flow pattern only accounted for roughly 7%. This strongly suggests that the length scales for nearshore flow variability extend over a much larger region than that covered by the instrument array. So, while local, shelf-scale vorticity (~ 1 km) may still prove to be an important mechanism, the dominant mechanisms driving variability are at large scales. Observations of low-frequency variability in sea surface height from the Honolulu Harbor time series appear correlated with variations in M2 amplitude. This suggests that nearshore variability may be associated with offshore mesoscale eddy activity either directly, via Doppler shifting due to the mesoscale velocity field or indirectly via changes in baroclinic activity due to modified stratification.

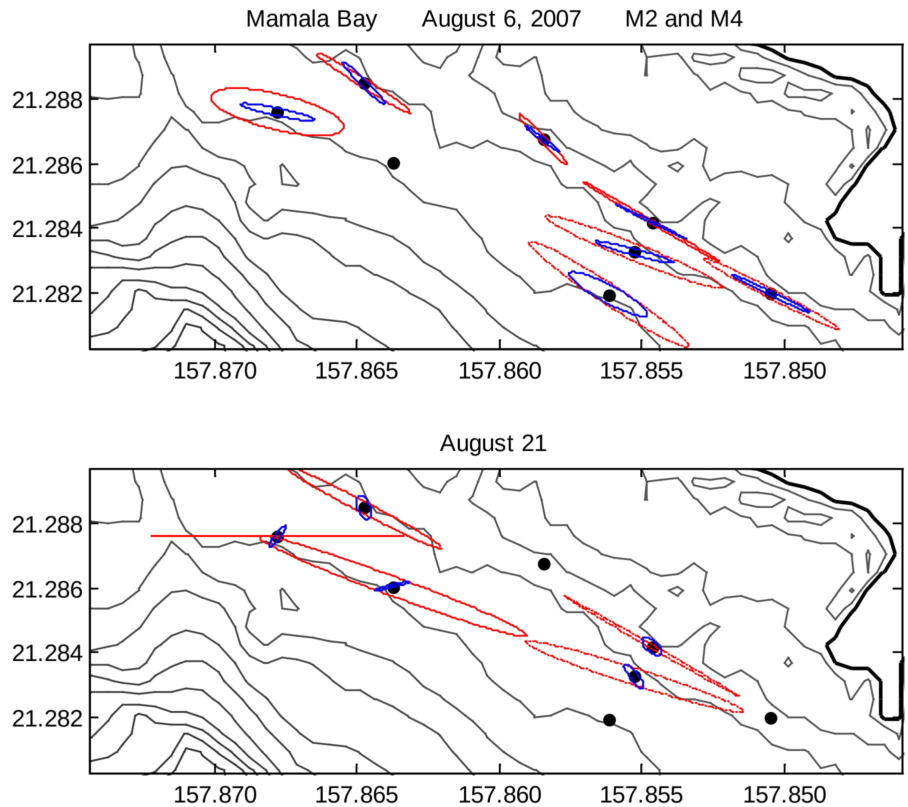


***Figure 3 – Current ellipses at 2007 observational array location for two instances. Red ellipses represent M2 current ellipses. Solid/dotted indicates rotational sense. Blue: M4 band ellipses.***

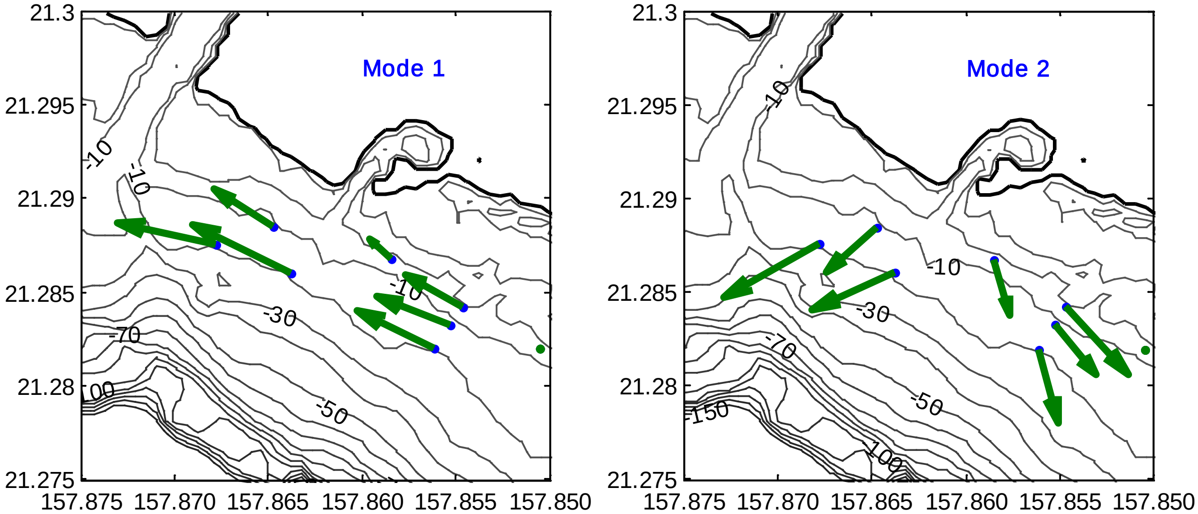


***Figure 5 – EOF modes 1 and 2 for 8/10/07-8/16/07. Mode 1 accounts for 75% of variance while Mode 2 corresponds to ~8%.***

Detailed analysis of thermal variability has also been carried out, with the primary focus on intermittent cold water intrusions near the bed. Statistical analysis of the multi-year Kilo Nalu 12m temperature record has shown that temperature cooling 'events' associated with shoaling internal tides are pervasive, occurring across tidal phases, current directions and seasons. Events tend to follow persistent periodic patterns occurring in clusters separated by days or weeks. AUV surveys, carried out in November 2006, targeted resolution of the alongshore baroclinic structure and identified high alongshore spatial variability in stratification indicating that boundary conditions large scale and nearshore models need to accurately represent spatial structure. Analysis of further AUV survey data from July 2007, combined with cabled and autonomous data, was able to establish a link between shoaling baroclinic energy from offshore and high frequency nearshore currents.

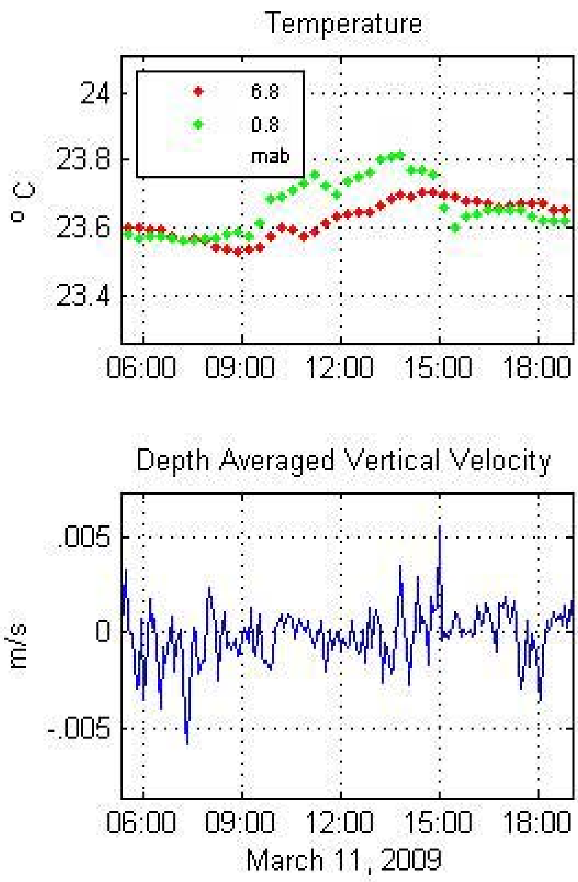


***Figure 5 - Top: Temperatures from the top and bottom thermistors of the 12 m KN t-chain. Bottom: Five-minute running mean of depth-averaged vertical velocity measured by the colocated ADCP.***

Analysis of diurnal temperature variability found that thermal inversions regularly occurred due to seafloor warming. The usual diurnal pattern shows increases in temperatures throughout the water column after sunrise, peaking in the early afternoon. Bottom waters typically warm faster than those at mid-depth. In ~30% of the observations, thermistor chain data indicated a midday temperature inversion with $\geq 0.025^{o}$ C between the lowest and highest thermistors, located 0.8 m and 6.8 m above bottom, respectively. The inversions are short-lived (60% last an hour or less). Their terminations generally coincide with sharp increases in the depth-averaged vertical velocities, suggesting instability and overturning. Figure 5 shows temperatures for a typical day. The inversion begins an hour after sunrise, terminating at mid-afternoon, accompanied by a distinct increase in the depth-averaged vertical velocities. Observations suggest that inversions occur as solar radiation heats the seafloor increasing near-bottom water temperatures. The consequent temperature inversion leads to destabilization of the water column, overturning and mixing. Clusters of stronger temperature inversions have also been observed, reaching up to $0.21^{0}$C and lasting up to 8 hours. Most are associated with storm conditions. In these cases, surface freshening stabilizes the density distribution inhibiting vertical mixing.

Analysis has also continued on extensive data sets collected as part of earlier ONR-funded work examining the near-bed structure of flow over highly rough bathymetry. The observations include data from deployments of the Rough Boundary Profiler (RBP) which employs a downward looking ADCP, profiling horizontally over a stretch of reef to generate a two-dimensional, phase-averaged velocity field over a 2m (cross-shore) x 1m (vertical) plane, as a function of wave-orbital amplitude. Analysis of this data along with development of a new wave-turbulence decomposition method applied within the wave boundary layer was the focus of a PhD thesis completed in Spring, 2009 (Bandet, 2009)

**IMPACT/APPLICATIONS**

Understanding of the relation between internal tide dynamics and nearshore processes is critical for accurate modeling of currents and sediment transport.in the coastal zone. An important objective of the ongoing work was to provide a qualitative assessment of the DELFT 3D model as a tool for predicting circulation and sediment transport in the spatially complex island/reef coastline. The modeling effort was unsuccessful for baroclinic flow at small scales highlighting model limitations in these regimes, particularly for complex coastlines with highly variable bathymetry. The observations supported by this project have identified low frequency offshore forcing as an important mechanisms in nearshore variability and characterized the associated effects, highlighting the complex relationship between offshore dynamics and currents in the nearshore zone. Effective modeling of waves, currents and sediment transport in the littoral zone of steep, complex coastlines will thus require accurate resolution of offshore baroclinic dynamics. Observations on the thermal variability have also identified seafloor heating and subsequent temperature inversions as an important mechanism in nearshore tropical waters, with potential implications on vertical fluxes and benthic biota.

Work on dynamics of near-bed, wave driven flow has suggested a new paradigm for flow over very rough, inhomogeneous bathymetry, where a broad spectral roughness distribution leads to varying length scales as a function of wave-orbital diameter. These ideas are forming the foundations for new friction/dissipation parameterizations that are critical for modeling flow over complex boundaries.

The ongoing work is also supporting extension of the cabled Kilo Nalu Observatory baseline infrastructure. Kilo Nalu has enabled real-time access to data, facilitating deployment of instruments that would otherwise be limited to short-term deployments. The initial Kilo Nalu infrastructure was deployed largely with support of earlier ONR grant.

**RELATED PROJECTS**

The work here is closely integrated with an NSF project, funded under the Coastal Ocean Processes (CoOP) program. The NSF work has funded an expansion of the Kilo Nalu Observatory including new baseline infrastructure. The work is examining the response of benthic boundary layer geochemical fluxes to physical forcing including surface waves and internal tides. The observations being undertaken as part of that work complement the broader scale field data collected for the ONR work. A comprehensive set of observations was initiated in July 2007 which coincided with the observations described earlier.

During the November 2006 experiment, two Kilo Nalu ADCPs serendipitously captured the signal associated with a small tsunami, generated by the November 15 Kuril Islands earthquake. Observations indicated that oscillations in pressure and velocity persisted for over two days. Analysis of the observations identified a significant component in the oscillations associated with coastal-trapped edge waves (Bricker et al, 2007).

The project is also benefiting from work carried out at Kilo Nalu via complementary projects. As part of the NSF CoOP project, a laser scanning altimeter (Tim Stanton, NPS) was deployed in Aug/Sept 2007. In addition, a sector scanning sonar collected data at the 10 m Kilo Nalu node in support of mine burial experiments (PIs R. Wilkens and M. Merrifield). AUV surveys carried out as part of this project and for the mine burial work are also obtaining sidescan imagery of the bedform morphology. ONR is also supporting development of AUV mapping resources for Kilo Nalu.

A newly funded NSF proposal began in 2009 (PI's Monismith, Koseff, Pawlak, Nash), examining the small scale turbulence associated with bores generated by shoaling internal tides. This work will complement and extend the broader scale observations supported by the project discussed above.

**REFERENCES**

M. L. Eich, M. A. Merrifield, and M. Alford, Structure and variability of semidiurnal internal tides in Mamala Bay, Hawaii, J. Geophys. Res., 109,C05010, doi:10.1029/2003JC002049, 2004.

V. Nunes and G. Pawlak, Observations of Physical Roughness Over a Coral Reef, J. Coastal Res., 24, 2B, 2008

**PUBLICATIONS**

The following articles and theses have been published under support of this project. In addition, two additional articles are presently in preparation focusing on wave boundary layer structure and thermal inversions.

M. Bandet, 2009: Dynamics of wave-induced boundary layers over very rough boundaries: Field observations over a stretch of coral reef. Ph.D. thesis, University of Hawaii, Honolulu, 197 pp.

J.D. Bricker, S. Munger, C. Pequignet, J.R. Wells, G. Pawlak, K. F. Cheung, ADCP observations of edge waves off Oahu in the wake of the November 2006 Kuril Islands tsunami, Geophys. Res. Lett., 34, L23617, doi:10.1029/2007GL032015, Dec. 2007

G. Pawlak, E. De Carlo, J. Fram, A. Hebert, C. Jones, B. McLaughlin, M. McManus, K. Millikan, F. Sansone, T. Stanton & J. Wells, "Development, Deployment, and Operation of Kilo Nalu Nearshore Cabled Observatory", IEEE OCEANS 2009 Conference, Bremen